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Infiltration Model for Center Pivot Irrigation on Bare Soil

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Abstract. *The marked reduction in infiltration rate caused by formation of a soil surface seal due to water droplet impact on bare soil is a well known phenomenon but is rarely considered in infiltration models, especially under center pivot irrigation. The objective of this study was to develop a soil infiltration model for center pivot sprinkler irrigation that incorporates the transient reduction in soil surface seal hydraulic conductivity as affected by soil and sprinkler characteristics and investigate the effect soil sealing characteristics and sprinkler selection have on infiltration depth. A sealing soil infiltration model was developed using an explicit finite difference solution scheme with a transient soil seal formation model, which is unique from other studies in that it explicitly uses droplet specific power as the driving factor for formation of a soil surface seal. The model was calibrated to four specific soils then applied to center pivot irrigation for five common center pivot sprinklers to evaluate the effect sprinkler selection has on infiltration depth. Due to the high susceptibility of the soils to surface sealing from water drop impact, the sprinkler with the largest wetted diameter was predicted to maximize infiltration depth.*

Keywords. *Sprinkler irrigation, Center pivot, Infiltration, Runoff, Soil surface seal, Droplet kinetic energy.*

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Introduction

The marked reduction in water infiltration rate of bare soils caused by raindrop impact has been recognized for over a century and has been extensively documented and studied over the past 70 years. The decrease in water infiltration rate of soils under droplet impact was first investigated by Duley (1939), Borst and Woodburn (1942), and Ellison (1945). McIntyre (1958) was the first to measure saturated hydraulic conductivity of soil surface seals created by raindrop impact. He found that the saturated hydraulic conductivity of the formed seals was a function of the soil, applied water depth and application rate. Seal saturated hydraulic conductivity was found to be 2 to 3 orders of magnitude less than for the underlying soil. Moldenhauer and Long (1964) found that infiltration rate was a function of soil properties, kinetic energy of the water drops and application intensity. They found that time for runoff to begin was a function of cumulative kinetic energy applied to the soil. Studies of Edwards (1967), Mannering (1967), Sharma (1980), Baumhardt (1985), Mahamad (1985), Thompson and James (1985), Betzalel et al. (1995) have demonstrated the influence droplet kinetic energy and water application rate has on infiltration rate into bare soils.

Studies documenting the significant effect water droplet impact have on the infiltration rate of bare soils led to the development of empirical models representing the transient nature of the saturated hydraulic conductivity of soil surface seals during a rainfall event. In general, these models expressed hydraulic resistance or saturated conductivity of the seal layer as an exponential decay function of time or applied droplet kinetic energy (Farrell and Larsen (1972); van Doren and Allmaras (1978); Linden (1979); Moore, et al. (1981); Brakensiek and Rawls (1983); Bosch and Onstad (1988); Baumhardt et al. (1990)). The models all include 3 or more parameters that need to be estimated from simulated rainfall infiltration experiments. These parameters have not been related to bulk soil properties to expand the models to other soils in general with the exception of Brakesiek and Rawls (1983) who developed a crust factor to account for crusted soil infiltration with the Green and Ampt (1911) infiltration model.

Nearly all of the research related to soil surface sealing has focused on rainfall conditions, but the same processes occur under sprinkler irrigation (von Bernuth and Gilley, 1985; Ben-Hur et al., 1995; Silva, 2006). Soil surface seal formation in combination with high water application rates under center pivot sprinkler irrigation exacerbates potential runoff and erosion hazard. Runoff under center pivot sprinkler irrigation is a well recognized problem (Undersander et al., 1985; DeBoer et al., 1992; Hasheminia, 1994; Ben-Hur et al., 1995; Silva, 2006), but is normally unseen because runoff often infiltrates before exiting the field boundary as only a small fraction of the field is irrigated (saturated) at a given time and/or runoff collects in low spots within the field.

The operational characteristics of center pivot sprinklers such as wetted diameter, application rate pattern shape and drop size distribution have been studied (e.g. Kincaid et al., 1996; Faci et al., 2001; DeBoer, 2001; Sourell et al., 2003; Playan et al., 2004; Kincaid, 2005;). However, studies evaluating the effect operating characteristics of a particular sprinkler have on infiltration, runoff, and erosion of specific soil types are limited (Undersander et al. 1985; DeBoer et al. 1992; Silva, 2006; King and Bjorneberg, 2011). Area weighted kinetic energy per unit volume of common sprinklers has been modeled by Kincaid (1996). King and Bjorneberg (2010) found that area weighted kinetic area does not represent the actual kinetic energy applied to the soil under center pivot sprinkler irrigation. They developed a methodology to calculate actual kinetic energy applied by center pivot sprinklers. With the wide range in operating characteristics of center pivot sprinklers currently available, the potential to select sprinklers that minimize runoff and erosion exist (King and Bjorneberg, 2011). However, data or

models relating sprinkler operating characteristics to runoff and erosion for specific soil types are limited. Models relating potential runoff to sprinkler peak application rate have been developed by Dillion et al. (1972), Slack (1980), Gilley (1984), DeBoer et al. (1988), Allen (1990), Wilmes et al. (1993) and Martin et al. (2010). Based on the work of Gilley (1984), von Bernuth and Gilley (1985) developed a methodology for estimating center pivot sprinkler irrigation runoff which considered infiltration rate reduction due to water drop impact on bare soil. Models currently available for estimating runoff under center pivot irrigation do not account for the effect of soil surface sealing on infiltration. Thus, such runoff estimations are of limited value under actual field conditions of arid regions where center pivot sprinkler irrigation on bare soil is generally required for crop germination and establishment.

The objective of this study was to develop an infiltration model for center pivot sprinkler irrigation that incorporates the transient reduction in soil surface seal hydraulic conductivity as affected by soil and sprinkler characteristics and investigate the effect soil sealing characteristics and sprinkler selection have on infiltration.

Model Development

Soil and Infiltration Data

Data used to develop and evaluate a sealing soil infiltration model were obtained from a published research study (Baumhardt (1985)) and laboratory rainfall simulator tests conducted at the USDA ARS Northwest Irrigation and Soils Research Laboratory located at Kimberly, Idaho. Baumhardt (1985) measured runoff from laboratory soil columns measuring 0.3 m tall and 0.35 m in diameter over a range of application rates and droplet kinetic energies per unit volume. The soil, an Atwood silty clay loam, was air dried, sieved and packed into the soil column to a density of 1.4 Mg m^{-3} . The columns were placed on a ramp with a 9% slope during rainfall simulation. The rainfall simulator produced droplets with kinetic energies of 20.0 and $27.5 \text{ J m}^{-2} \text{ mm}^{-1}$ with a range of application rates from 20 to 90 mm h^{-1} . Rainfall simulation duration ranged from 60 to 120 min.

Laboratory rainfall simulator tests were conducted on three soils, Portneuf silt loam, Walla Walla silt loam, and Turbyfill fine sandy loam, using soil packed in a box measuring 0.3 m wide and 1.0 m long and placed on a 5% slope. The soil was air dried, sieved and packed to a bulk density of 1.3 to 1.4 Mg m^{-3} for the Portneuf silt loam and Turbyfill fine sandy loam and 1.05 to 1.15 Mg m^{-3} for the Walla Walla silt loam. The rainfall simulator produced droplets with kinetic energies of 3.9 and $8.5 \text{ J m}^{-2} \text{ mm}^{-1}$ using fall heights of 0.3 and 1.0 m, respectively. Water application rates ranged from 100 to 215 mm h^{-1} . Rainfall simulation duration ranged from 30 to 60 min. Runoff volume was measured by continuously recording the cumulative weight of runoff water. Total infiltrated volume was determined by weighing the soil box immediately before and after rainfall simulation. Water application rate was calculated by dividing the sum of infiltrated and runoff volumes by time of application. Infiltration rate was calculated as the difference between water application rate and runoff rate, neglecting soil surface storage. Soil texture analysis was determined for each soil using the hydrometer method (table 1).

Soil water retention characteristics of the soils used in this study were estimated based on soil texture using the pedotransfer functions of Saxton and Rawls (2006). The Brook and Corey (1964) relationships were used to model soil hydraulic properties as a function of soil water potential. Parameters for the Brooks and Corey (1964) soil water relationships were estimated by fitting them to values of soil water potential versus soil water content estimated by the Saxton and Rawls (2006) pedotransfer functions. Saturated water content was taken as 80% of pedotransfer function predicted porosity. Other infiltration studies have estimated saturated water

Table 1. Particle size fractions for the soils used in the study.

Soil Name	Particle Size Fraction (%)		
	Sand	Silt	Clay
Atwood Silty Clay Loam	12	60	28
Portneuf Silt Loam	14	65	21
Walla Walla Silt Loam	13	63	24
Turbyfill Fine Sandy Loam	48	37	15

content as 62 to 92% of saturated water content (Mein and Larson, 1973; Slack, 1980; Moore, 1981; Römkens et al., 1985; Eisenhauer et al., 1992). Water entry pressure head for soil wetting was estimated as one-third the air entry pressure predicted by the Saxton and Rawls (2006) pedotransfer function. Saturated hydraulic conductivity was determined by fitting the infiltration model absent soil surface sealing to infiltration data with the surface protected from droplet impact. Values used to characterize soil water retention properties of the soils are given in table 2.

Infiltration Model

Infiltration was modeled using a one dimensional fully implicit finite difference numerical solution to Richard's equation (Rathfelder and Abriola 1994; Shahraiyini and Ashtiani, 2009). The Thomas Algorithm (Thomas, 1949) was used to solve the tridiagonal matrix of simultaneous equations. The model was written in Microsoft Visual Basic. Soil profile depth increments were 1 mm and time increments were 0.01 min for the first 3 min of infiltration then 0.1 min thereafter. Convergence criteria for each time step was less than 0.2 mm of head change between subsequent iterations for any node in the soil profile. Developing soil surface seal hydraulic properties were assumed to be uniform over a 5 mm depth below the soil surface surface (Moore and Larson, 1980; Moore, 1981; Moore et al., 1981; Ahuja, 1983; Baumhardt et al., 1990; Ruan et al., 2001, Assouline, 2004). The soil profile was assumed to be infinitely uniform below the surface seal with constant hydraulic properties equivalent to the soil surface layer prior to infiltration.

Table 2. Infiltration model parameters used to characterize the hydraulic properties of the soils used in this study.

Model Parameter	Atwood Silty Clay Loam	Portneuf Silt Loam	Walla Walla Silt Loam	Turbyfill Fine Sandy Loam
Porosity	0.48	0.48	0.51	0.47
Residual Moisture Content, % volume	0.10	0.11	0.13	0.09
Saturated Moisture Content, % volume	39.7	38.6	40.5	38.0
Initial Soil Water Potential, mm	-1800000	-1000000	-1000000	-500000
Water Entry Head, mm	-300	-451	-443	-106
Brooks-Corey Exponent (λ)	0.158	0.32	0.30	0.36
Saturated Hydraulic Conductivity*, mm h ⁻¹	6.0	9.0	3.5	37.5
Empirical soil seal resistance factor, S_f	0.02	0.06	0.04	0.07

*Equals K_i in equations 2 and 3.

Soil Surface Sealing Model

Specific power or SP ($W\ m^{-2}$) also termed kinetic energy flux density (Thompson and James, 1985) can be calculated for a rainfall simulator with constant application rate and drop kinetic energy as:

$$SP = \frac{KE_d \cdot R}{3600} \quad (1)$$

where KE_d is droplet kinetic energy per unit volume ($J\ m^{-2}\ mm^{-1}$) and R is application rate ($mm\ h^{-1}$). Cumulative kinetic energy applied to a soil surface can then be calculated as specific power multiplied by time in seconds.

Transient soil surface seal development has traditionally been modeled using an exponential decay function of cumulative kinetic energy ((Farrell and Larsen (1972); van Doren and Allmaras (1978); Linden (1979); Moore, et al. (1981); Brakensiek and Rawls (1983); Bosch and Onstad (1988); Baumhardt et al. (1990)) of the general form:

$$K(t) = K_f + (K_i - K_f) \cdot e^{-c \cdot E} \quad (2)$$

where K is hydraulic conductivity ($mm\ h^{-1}$), K_f is final saturated hydraulic conductivity ($mm\ h^{-1}$) of the soil surface seal after an extended period of droplet impact absent the effect of seal erosion, K_i is initial satiated hydraulic conductivity of the surface soil ($mm\ h^{-1}$), c is an empirical parameter that represents soil structural stability ($m^2\ J^{-1}$), and E is some representation of cumulative droplet energy ($J\ m^{-2}$). The empirical parameter c is required in the model to incorporate inherent differences between soils concerning susceptibility to surface seal formation due to soil texture, salinity, organic matter, cropping history, and tillage history (Bosch, 1986).

Equation 2 was incorporated into the infiltration model by calculating a reduced hydraulic conductivity for the surface seal (top 5 mm) at each time step by representing E as SP multiplied by time in seconds. Application of the infiltration model to rainfall simulator data sets using the exponential decay function (eq. 2) tended to underpredict the infiltration rate under low levels of specific power (i.e., low rainfall intensity and/or low droplet kinetic energy). Based on this observation, King and Bjorneberg (2012) developed a similar equation to describe transient soil formation:

$$K(t) = K_f + \frac{(K_i - K_f)}{1 + S_f (SP \cdot t)^{1.2}} \quad (3)$$

where S_f is a dimensionless empirical soil factor that represents resistance to surface seal formation, consistent with the use of c in equation 2, and t is time in seconds. Equation 3 was modified in this study to account for the transient nature of SP and R as a center pivot irrigation system passes over a stationary point on the soil surface. The resulting equation for transient soil surface seal formation used to model center pivot irrigation was:

$$K(t) = K_f + \frac{(K_i - K_f)}{1 + S_f \left(\int_0^T SP(t) \cdot dt \right)^{1.2}} \quad (4)$$

where T (seconds) is the time of the irrigation event.

Model Fit Criteria

Infiltration model goodness of fit was quantified by examining the sum of squared difference between model predicted value and data relative to the sum of squared difference between data and mean data value which is termed model efficiency (*ME*). Model efficiency (Nash and Sutcliffe 1970; Bjorneberg et al. 1999) is defined as:

$$ME = 1 - \frac{\sum (y_i - y_{pred})^2}{\sum (y_i - y_{ave})^2} \quad (5)$$

where y_i is the i th data value, y_{pred} is model predicted value for y_i and y_{ave} is the mean of the data values. Model efficiency was used to optimize model parameters and quantify goodness of fit. Model efficiency is similar to the correlation coefficient associated with linear regression in that its value ranges from $-\infty$ to 1. A value of 1 means the model is a perfect fit to the data but a negative *ME* value signifies that the data mean is a better estimate of the data than the model. Use of *ME* alone can be misleading as it does not take into account other factors that enter into determining model goodness of fit. For example with infiltration models, reliable estimate of time to ponding is important but is not quantified by using *ME* alone. Model parameters were determined based on maximizing *ME* but adjusted when there was considerable variability in the data to provide an improved estimate of mean time to ponding with little quantitative decrease in the value of *ME*.

Model Calibration

The three parameters used in modeling transient seal development (equation 3) were determined by fitting the infiltration model to the data for each of the four soils over the range of *SP* values in the data sets. The value for saturated hydraulic conductivity for each soil was determined by trial and error fitting of the infiltration model to maximize *ME* when the soil surface was protected from droplet impact. The value obtained for saturated hydraulic conductivity was held constant for all subsequent model simulations under transient soil seal development due to varying kinetic energy levels and application intensities (*SP*) for each soil. The values for K_f and S_f were then determined jointly for each soil by trial and error fitting the two parameters to maximize *ME* for each specific power.

Sprinkler Characteristics

Sprinklers used in this study and corresponding operating pressures, nozzle sizes and flow rates are listed in table 3. The R3000¹ sprinklers (Nelson Irrigation Corp., Walla Walla, WA) used rotating plates with grooves to breakup the nozzle jet and create discrete streams of water leaving the plate edge. The R3000 sprinkler with the brown plate had ten grooves with multiple trajectories angles and widths. The R3000 sprinkler with the red plate had six grooves of equal trajectory angle (12°) and width. R3000 sprinkler with the orange plate had eight grooves with multiple trajectories angles and widths. The R3000 sprinklers had plate rotational speeds of 2 to 4 revolutions per minute. The S3000 sprinkler (Nelson Irrigation Corp., Walla Walla, WA) used a rotating purple plate with grooves to breakup the nozzle jet. The rotating plate had six grooves with trajectories from 12 to 20° and a rotational speed of 400 to 500 revolutions per

¹ Mention of trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the authors or their institutions and does not imply approval of product to the exclusion of others that may be suitable.

Table 3. Operating characteristics for the five sprinklers used in this study.

Parameter	Sprinkler				
	D3000	S3000	R3000 Red Plate	R3000 Brown Plate	R3000 Orange Plate
Nozzle Diameter, mm	8.14	8.14	7.54	7.54	7.54
Operating Pressure, kPa	103	103	138	138	138
Flow Rate*, L min^{-1}	43.4	43.4	42.7	42.7	42.7
Average Application Rate, mm h^{-1}	104.0	61.8	51.0	47.6	28.6
Peak Application, mm h^{-1}	165.3	97.4	84.6	88.5	47.3
Kinetic Energy, $\text{J m}^{-2} \text{mm}^{-1}$	11.8	10.9	12.1	9.7	13.2
Average Specific Power, W m^{-2}	0.340	0.188	0.171	0.129	0.109
Peak Specific Power, W m^{-2}	0.602	0.263	0.233	0.191	0.149

*Based on Manufacturer's data.

minute. The D3000 sprinkler (Nelson Irrigation Corp., Walla Walla, WA) had a fixed flat plate to breakup the nozzle jet into discrete water drops. Sprinkler operating pressures were selected to be representative of field installations on center pivot sprinkler irrigation systems in southern Idaho. Sprinkler nozzle sizes were selected to provide nearly equal flow rates at the given operating pressures based on manufacturer data. Sprinkler flow rate was representative of that found near the end of the lateral on 390 m long center pivot sprinkler irrigation systems in southern Idaho.

Center pivot composite application rate and specific power profiles for sprinklers spaced 3m along the lateral were determined using the methodology described by King and Bjorneberg (2010). Briefly, sprinkler drop size and velocity were measured at 1 m radial increments from the sprinkler in the laboratory using a laser disdrometer (King et al., 2010). Sprinkler radial application rate profiles were also measured in the laboratory. These data were used to compute sprinkler radial specific power and droplet kinetic energy profiles. A sprinkler pattern overlap model was used to compute no wind composite water application rate and specific power profiles from sprinklers spaced 3 m along a single lateral using the laboratory determined sprinkler radial water application and specific power profiles. The average composite water application rate profile between sprinklers was used to determine the travel time of a center pivot lateral to apply 25.4 mm of water. Kinetic energy applied per unit application water depth was determined by integrating the average composite specific power profile between sprinklers over the time interval required to apply 25.4 mm of water and dividing the value by 25.4 mm. The resulting composite water application rate and specific power profiles for each sprinkler are shown in figures 1 and 2, respectively. Peak and average water application rate and specific power and droplet kinetic energy per mm water application for each sprinkler when spaced 3 m along the center pivot lateral are given in table 3.

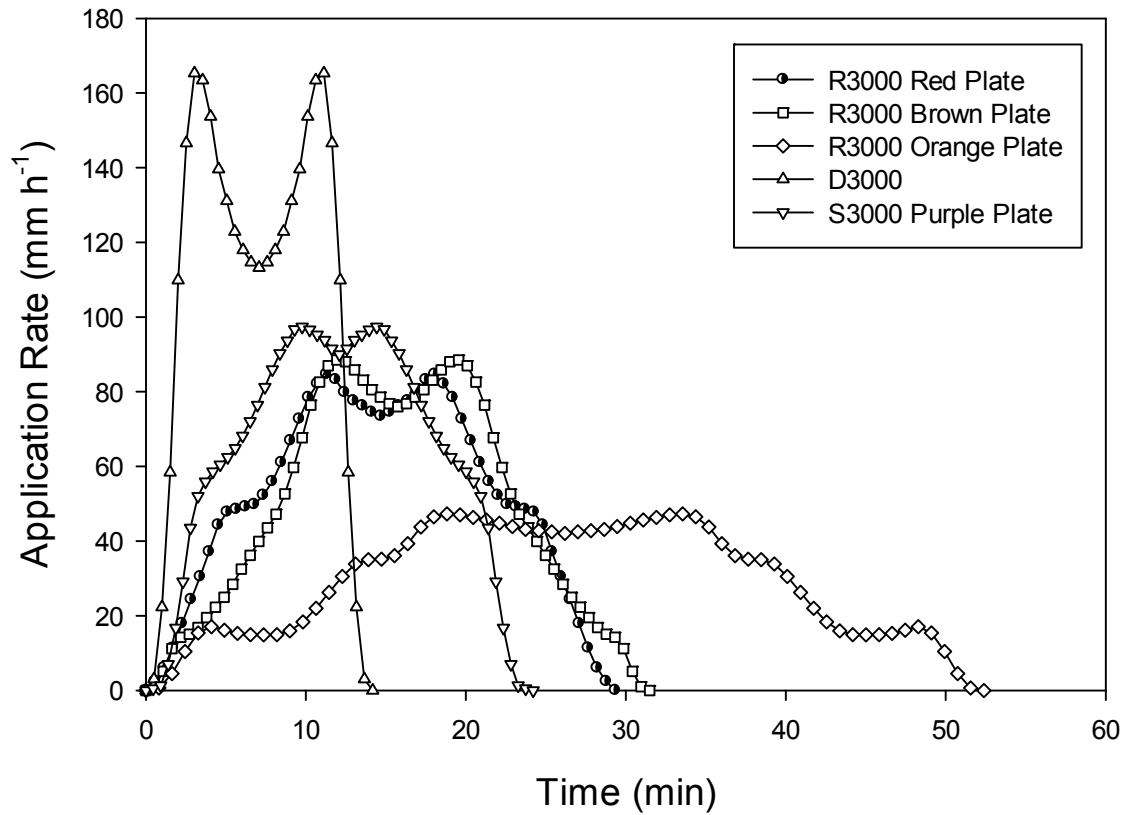


Figure 1. Average composite application rate profile for five sprinklers used in this study spaced 3m along a center pivot lateral.

Results and Discussion

The sealing soil infiltration model was fit to infiltration rate data for each soil when the soil surface was protected from droplet impact to determine the value of saturated hydraulic conductivity. The value obtained for saturated hydraulic conductivity was held constant for all subsequent model simulations under transient soil seal development due to varying kinetic energy levels and application intensities. The infiltration model without surface sealing provided a good fit to the infiltration data for each soil based on the values of ME obtained (fig. 3) and prediction of time of ponding. The lower value for ME for the Atwood silty clay loam soil at 41 mm h⁻¹ application rate test is an artifact of the ME parameter and scatter in the infiltration data rather than poor model fit to the infiltration data. For the Atwood soil, an average of the infiltration data provides a reasonable representation of infiltration rate, which is the basis for the denominator in equation 5. The infiltration model provides an improved fit to the data compared to an average value, hence the value of ME is between 0 and 1, but the improvement over an average is relatively small. Saturated hydraulic conductivity values for each soil that provided a good overall fit to the infiltration data are listed in table 2.

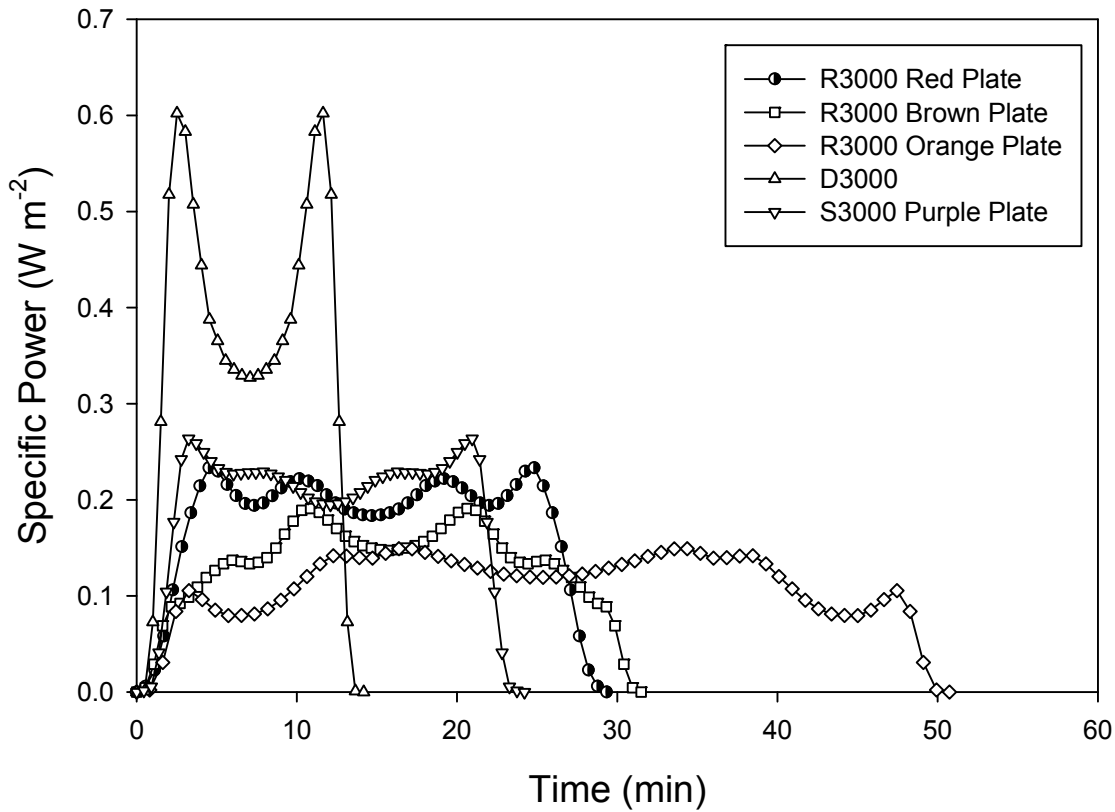


Figure 2. Average composite specific power profile for the five sprinklers used in this study spaced 3m along a center pivot lateral.

The sealing soil infiltration model provided a good fit to the infiltration data for each soil under varying levels of SP . The results for the Atwood silty clay loam soil at four levels of specific power are shown in fig. 4. The value for S_f (eqn. 3) was held constant at 0.02 and the value of K_f (eqn. 3) ranged from 0.005 to 0.04 mm h⁻¹. The fit of the model was slightly reduced at higher levels of specific power due to an apparent increase in final infiltration rates with specific power. Assouline and Ben-Hur (2006) found that final infiltration rate and soil loss increased with rainfall intensity (specific power) and became more prominent with slope steepness, consistent with several other study results (Assouline and Ben-Hur, 2006). The increase in final infiltration rate (seal conductivity) with increasing rainfall intensity can be due to a thinner and less compacted seal layer resulting from higher erosion of the soil surface and lower normal component of drop impact force (Assouline and Ben-Hur, 2006). Another possibility is that as slope increases, more fine particles susceptible to be washed-in and clog pores below the surface are transported by overland flow, thus reducing the probability of pore clogging within the seal layer and, consequently, thickness and final infiltration rate (Assouline and Ben-Hur, 2006). The surface seal model used in this study (eqn. 3) does not account for erosion of the seal layer, potentially the cause for the reduced fit to the infiltration data of Baumhardt (1985) at higher specific powers. The sealing soil infiltration model provided an excellent fit to the infiltration data of the Walla Walla silt loam soil under four values of SP (fig. 5). Results for the other two soils were similar ($ME > 0.80$) to those for the Atwood and Walla Walla soils. Values for S_f (eqn. 3) for each soil used in the sealing soil infiltration model are listed in table 2.

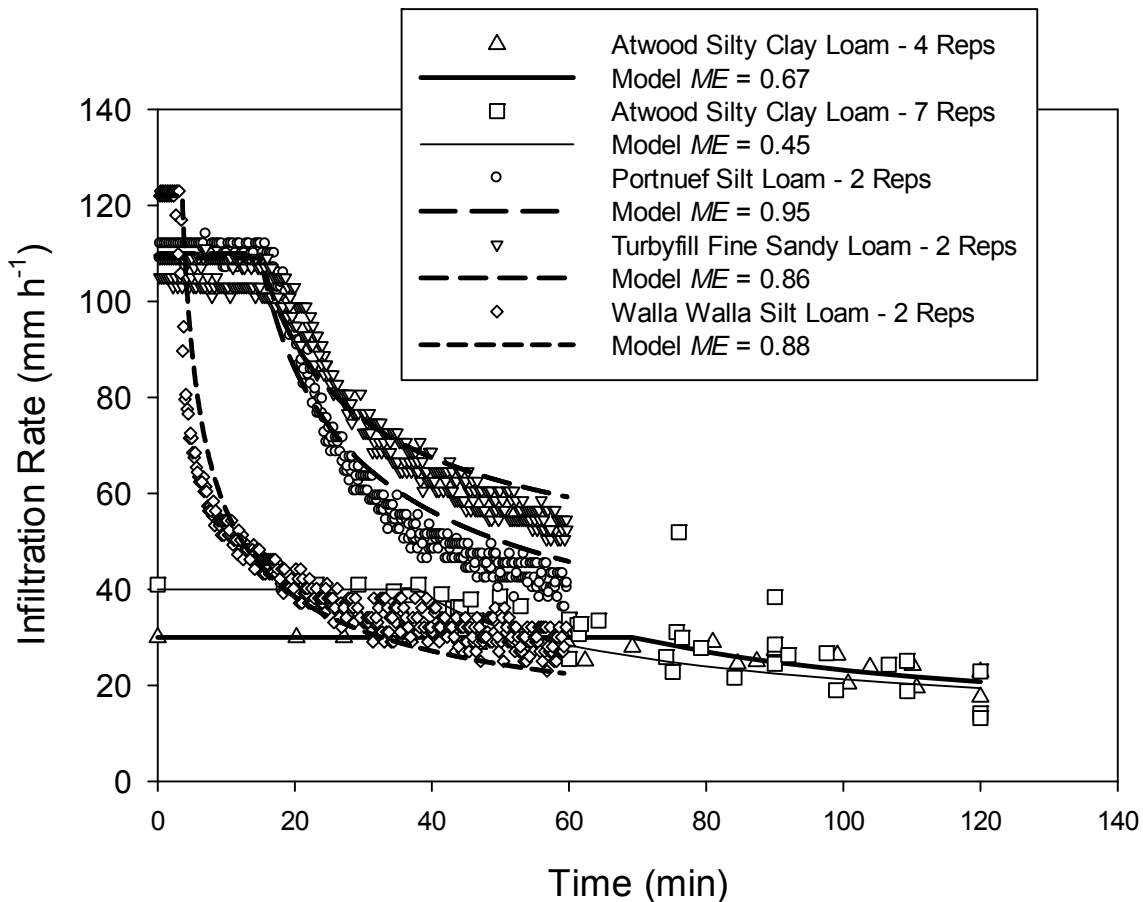


Figure 3. Model prediction of infiltration into each soil compared to measured infiltration under rainfall simulator when the soil surface was protected from droplet impact.

Final infiltration rate (K_f , eqn. 3) for each soil was found to decrease with increasing specific power, figure 6. This can be due to a thicker soil surface seal and an increase in surface seal density with greater specific power applied to the soil surface. The finite difference model used a constant 5 mm soil surface seal thickness. Thus, any change in surface seal thickness is modeled as a change in final hydraulic conductivity. A power relationship between K_f and SP provided a good fit to the infiltration data for each soil (fig. 6) with the exception of the Portneuf silt loam where a linear relationship provided a greater correlation coefficient. It may be possible to develop a relationship between K_f , SP , and soil texture in general, but more infiltration data is needed to determine if such a relationship exists. The effect of specific power on K_f is consistent with the results of Shainberg and Singer (1988) who found that final infiltration rate decreased with increasing droplet fall height for an application rate of 40 mm h⁻¹.

The surface sealing infiltration model calibrated to rainfall simulator data was used to evaluate the effect of sprinkler selection on infiltration for each soil. Sprinkler composite application rate (fig.1) and specific power (fig. 2) profiles as a function of time were used in the model rather than constant application rate and specific power of a rainfall simulator. The relationships between specific power and K_f shown in figure 6 were used in the model. With center pivot irrigation, specific power is a function of time rather than a constant with a rainfall simulator. To

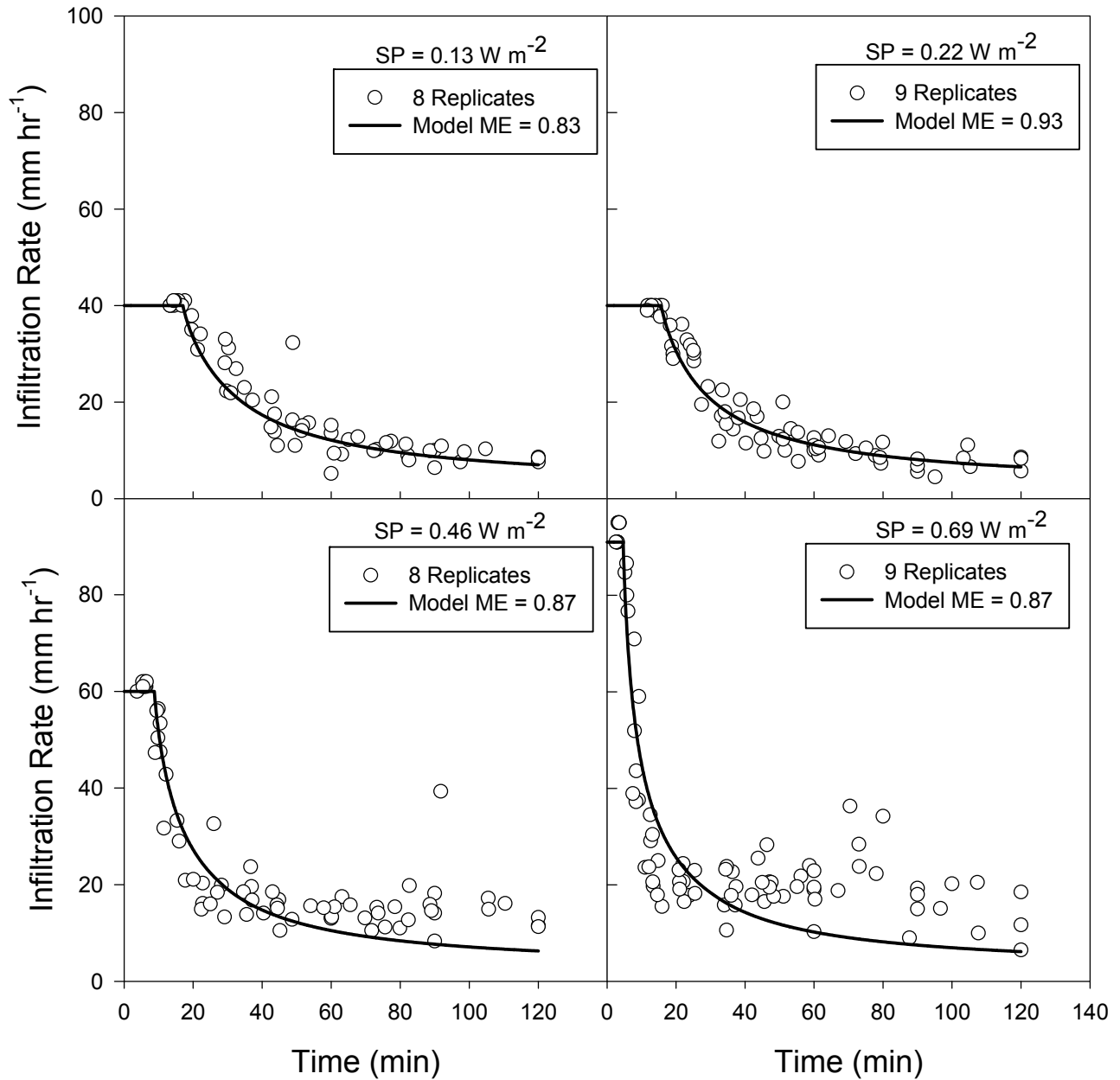


Figure 4. Infiltration model fit to measured infiltration from soil columns of Atwood silty clay loam soil reported by Baumhardt (1985) under four levels of specific power applied by simulated rainfall.

adapt the model to this feature of center pivot sprinkler irrigation, K_f was allowed to decrease with time (increasing SP) to a minimum value (maximum SP) and held constant for the remainder of the irrigation event. This implicitly assumes that peak specific power determines K_f for the soil under transient conditions.

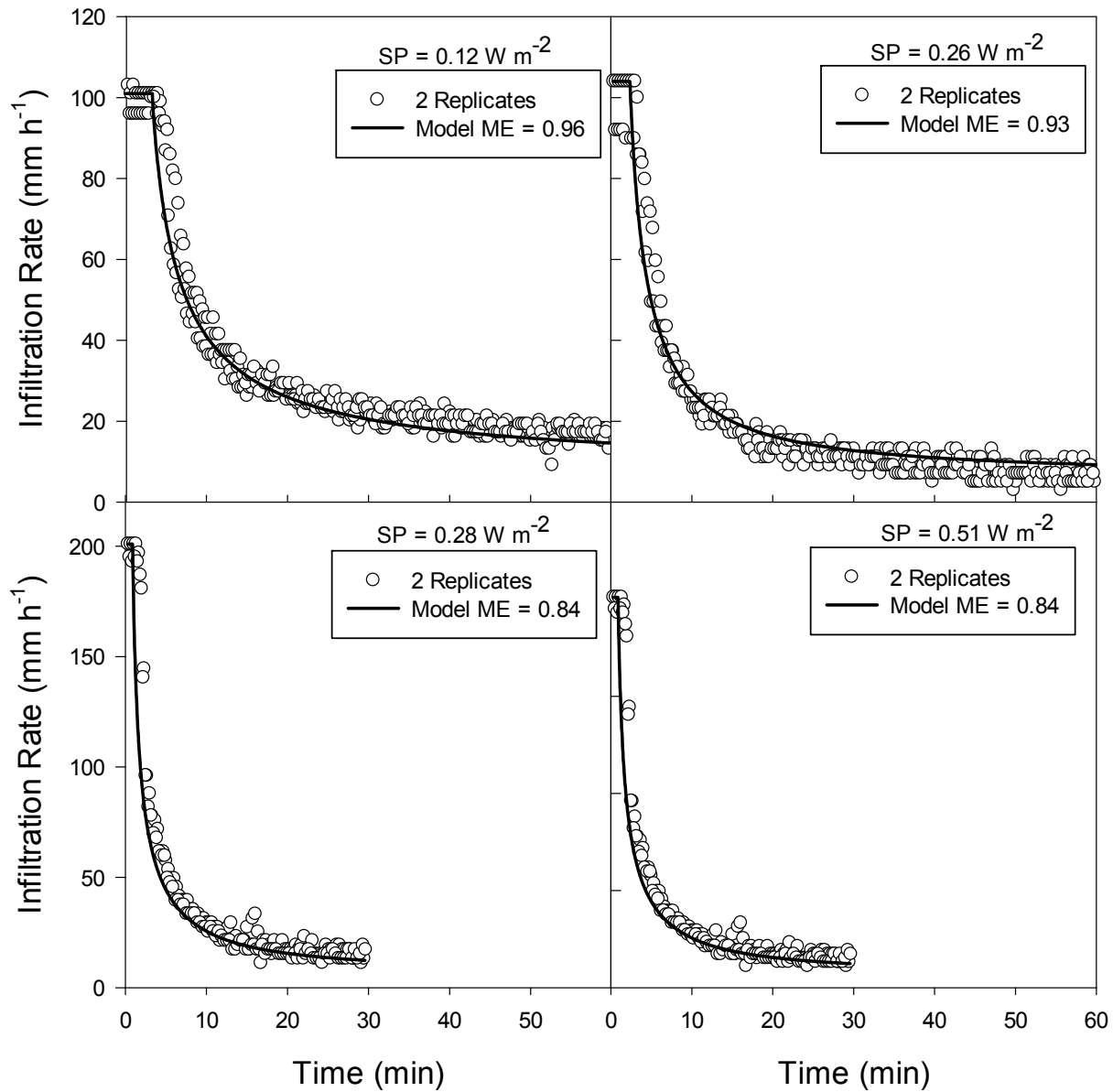


Figure 5. Infiltration model fit to measured infiltration for Walla Walla silt loam soil at four levels of specific power applied by laboratory simulated rainfall.

The effect surface sealing has on predicted infiltration rate for the R3000 red plate sprinkler with the Atwood silty clay loam soil is shown in figure 7 for both a 25.4 mm and 15.0 mm irrigation water application event. Predicted infiltration with soil surface sealing is 3.6 mm less for the 25.4 mm application and 2 mm for the 15.0 mm application than predicted for no surface seal, table 4. Potential runoff exists with or without surface seal formation due to the low saturated hydraulic conductivity of the Atwood silty clay loam soil (fig. 7). Predicted potential runoff is 43% for the 25.4 mm application and 27% for the 15.0 mm application with the effect of surface sealing and 29% and 13%, respectively, without surface sealing. Decreasing irrigation application depth decreases potential runoff and potentially increases irrigation water application efficiency with or without surface sealing.

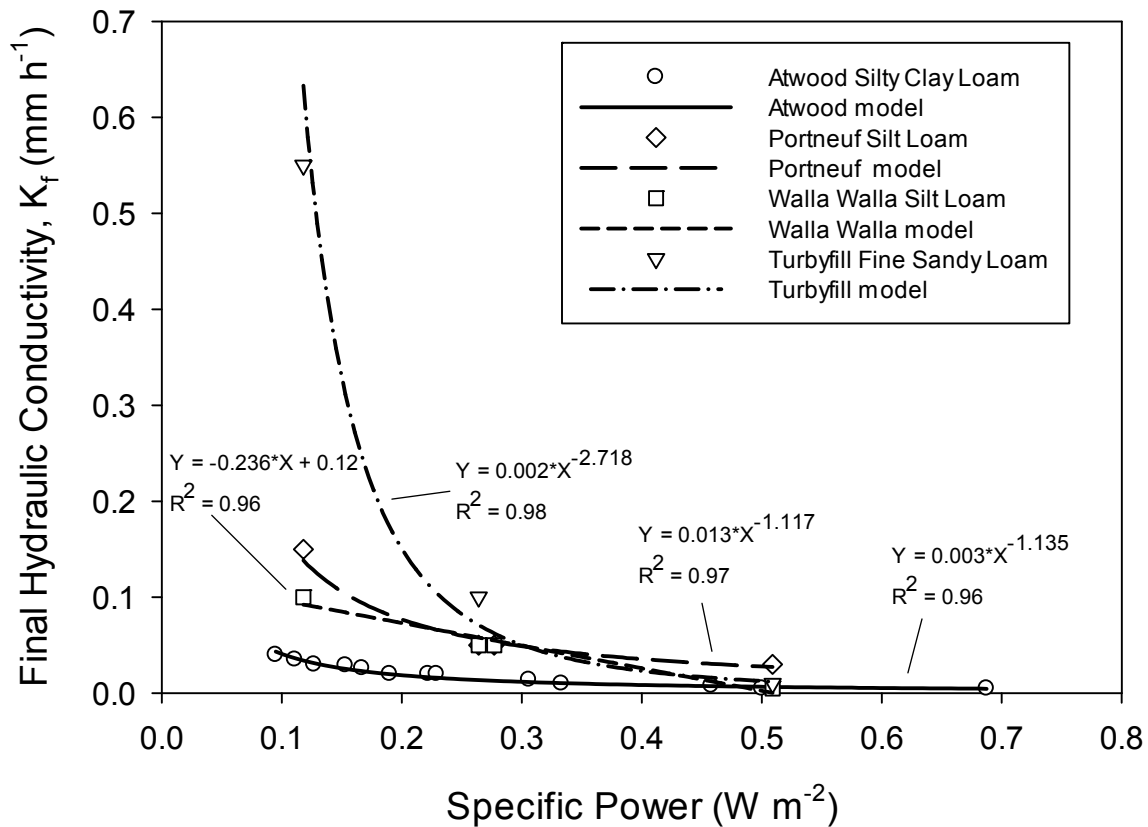


Figure 6. Relationship between final hydraulic conductivity of surface seal and specific power for each soil used to model infiltration under surface seal formation in this study.

The effect sprinkler wetted radius has on infiltration both with and without surface sealing for the Atwood silty clay loam soil is shown in figure 8 where the D3000 sprinkler is contrasted with the R3000 orange plate sprinkler. Predicted infiltration is 9.8 mm for the D3000 sprinkler and 19.2 mm for the R3000 orange plate sprinkler (table 4) for a 25.4 mm application event with the effect of surface sealing, a 96% difference in infiltration and hence potential runoff. Conventional sprinkler irrigation wisdom suggests that a sprinkler with small drops (minimum droplet kinetic energy) should be used on a sealing soil such as the Atwood silty clay loam, to maximize infiltration and minimize runoff. However, the infiltration model does not predict this to be the case. The Atwood silty clay loam soil is highly susceptible to surface sealing as hydraulic conductivity of the seal decreases by two orders of magnitude with as little and 0.1 W m^{-2} of applied SP , figure 6. All the sprinklers used in this study have greater SP and consequently form a soil surface seal. Given that a surface seal is going to form, spreading out the irrigation event over time and minimizing application rate maximizes infiltration, which is what the model predicts, regardless of kinetic energy. Thus, the R3000 orange plate sprinkler with $13.2 \text{ J m}^{-2} \text{ mm}^{-1}$ of applied kinetic energy (table 3), which is 12% greater than the D3000 sprinkler, results in the greatest predicted infiltration for the Atwood silty clay loam soil.

Predicted infiltration depth for each soil and sprinkler combination is shown in table 4. The results are consistent across all soils in that sprinkler wetted diameter determines infiltration

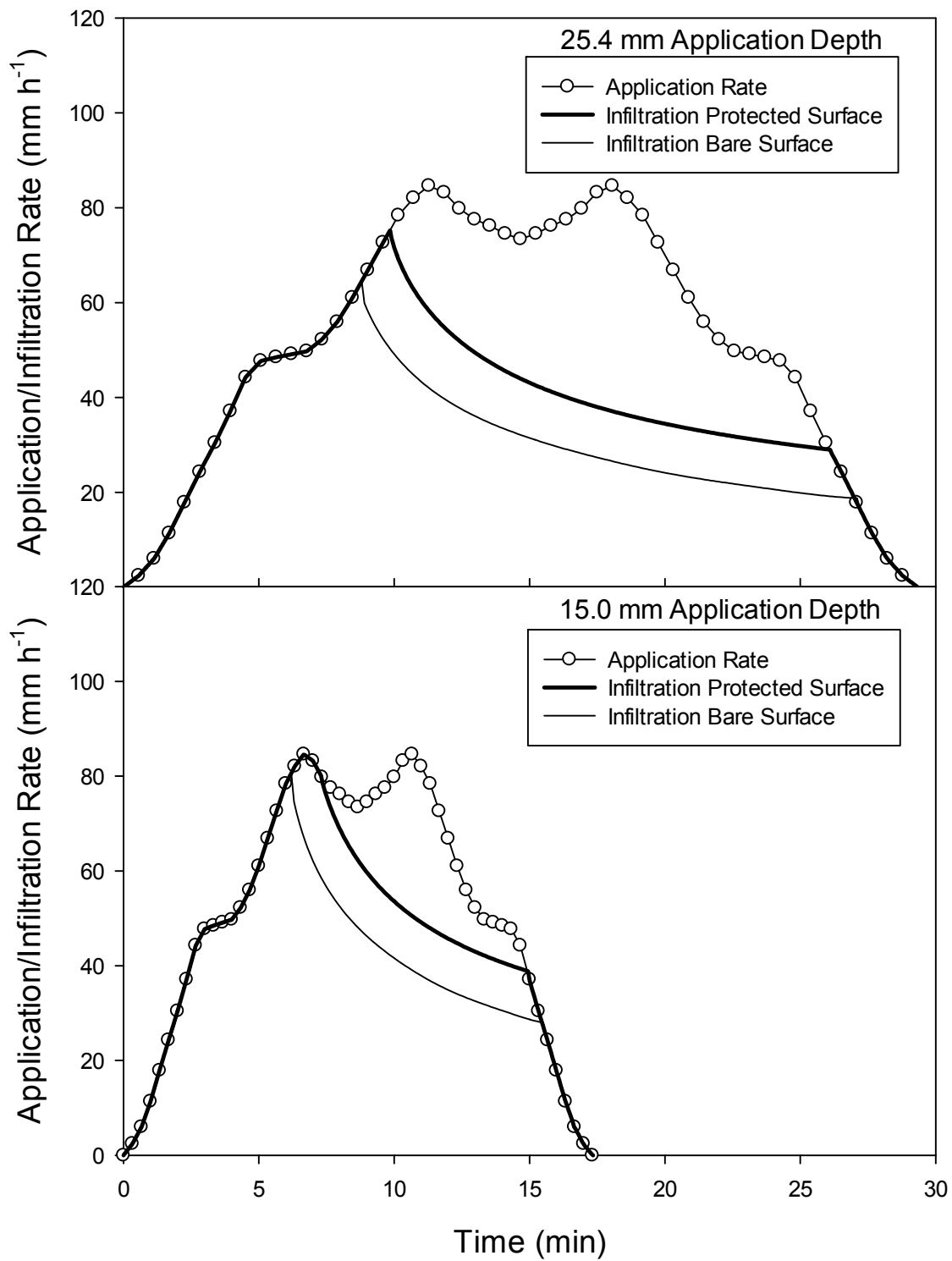


Figure 7. Model predicted infiltration rate for the Atwood silty clay loam soil under center pivot irrigation with the R3000 red plate sprinkler for protected and bare soil surface conditions and application depths of 25.4 and 15.0 mm.

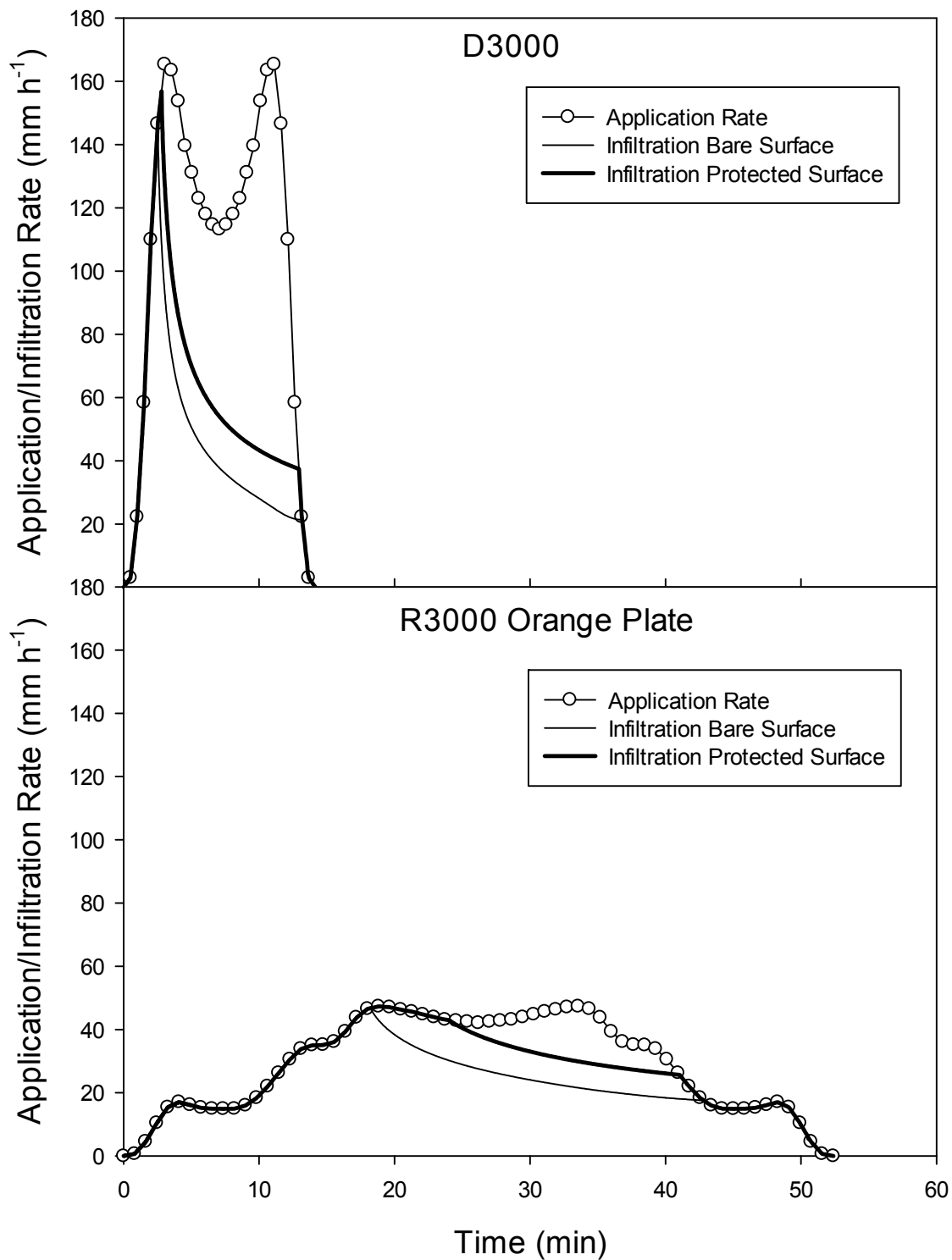


Figure 8. Model predicted infiltration rate for the Atwood silty clay loam soil under center pivot irrigation with the D3000 and R3000 orange plate sprinkler for protected and bare soil surface conditions and an application depth of 25.4 mm.

Table 4. Infiltration model predicted infiltration in mm for each of the five sprinklers and soil used in this study.

Sprinkler	Application Depth = 25.4 mm		Application Depth = 15.0 mm	
	Protected Soil	Bare Soil	Protected Soil	Bare Soil
----- Atwood Silty Clay Loam -----				
D3000	13.1	9.8	9.7	7.9
S3000	16.4	13.3	11.9	10.2
R3000 Red Plate	18.0	14.4	13.0	11.0
R3000 Brown Plate	18.0	15.2	12.8	11.4
R3000 Orange Plate	22.7	19.2	14.9	13.8
----- Portneuf Silt Loam -----				
D3000	20.7	11.4	13.9	9.6
S3000	24.6	16.3	15.0	12.7
R3000 Red Plate	25.4	17.7	15.0	13.5
R3000 Brown Plate	25.4	19.0	15.0	14.0
R3000 Orange Plate	25.4	23.5	15.0	15.0
----- Walla Walla Silt Loam -----				
D3000	13.6	6.7	10.1	6.0
S3000	16.9	11.3	12.3	8.9
R3000 Red Plate	18.5	12.5	13.3	9.7
R3000 Brown Plate	18.5	13.4	13.2	10.3
R3000 Orange Plate	23.1	17.4	15.0	12.7
----- Turbyfill Fine Sandy Loam -----				
D3000	23.7	10.9	15.0	9.4
S3000	25.4	15.5	15.0	12.5
R3000 Red Plate	25.4	16.7	15.0	13.3
R3000 Brown Plate	25.4	19.0	15.0	14.6
R3000 Orange Plate	25.4	23.6	15.0	15.0

depth for each soil and application depth under surface sealing conditions. All the soils used in this study were susceptible to formation of a soil surface seal by droplet impact that results in surface seal infiltration rates two to three orders of magnitude less than saturated hydraulic conductivity of the bulk soil profile. The drastic reduction in hydraulic conductivity of the surface seal occurs at *SP* values below that provided by the sprinklers used in this study. If a center pivot sprinkler irrigation system is operated over a bare soil at the application rates used in this study, a surface seal is going to form, and the only way to maximize infiltration depth is to apply the water over the largest time interval possible.

Summary

A sealing soil infiltration model was developed using an explicit finite difference solution scheme with a transient soil seal formation model, which is unique from other studies in that it explicitly uses specific power as the driving factor for formation of a soil surface seal. The form of the transient seal formation model is also unique in that it is expressed as a rational function of specific power rather than an exponential decay function of cumulative droplet kinetic energy, water applied or time. The advantage of using specific power is that application rate as well as

droplet kinetic energy are implicitly incorporated into soil surface seal formation. The utility of using specific power as the driving factor is demonstrated by application and performance of the sealing soil infiltration model across for both rainfall simulation and center pivot sprinkler irrigation.

The transient soil seal formation model uses three parameters; initial satiated hydraulic conductivity of the soil, final saturated hydraulic conductivity of the soil surface seal, and an empirical soil factor that represents the susceptibility of the soil to aggregate breakdown under droplet impact. Final saturated hydraulic conductivity of the soil surface seal was found to be well correlated with specific power for the soil used in this study. The soil factor was found to depend upon soil only. Predetermined estimation of the three model parameters is difficult, but could potentially be achieved by the development of correlations with soil physical parameters.

The infiltration model was used to predict infiltrated depth for five common center pivot sprinklers with four soils having high susceptibility to soil surface seal development from droplet impact. Due to the high susceptibility of the soils to surface sealing from water drop impact, the sprinkler with the largest wetted diameter was predicted to maximize infiltration. If a center pivot sprinkler irrigation system is operated over a bare soil at the application rates used in this study, a surface seal is going to form, and the only way to maximize infiltration depth is to apply the water over the largest time interval possible.

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